Study of Kuroshio Intrusion and Transport using Moorings and EM-APEX Floats in QPEU Experiment

Ren-Chieh Lien
Applied Physics Laboratory
University of Washington
1013 NE 40th Street
Seattle, Washington 98105
Phone: (206) 685-1079 fax: (206) 543-6785 email: lien@apl.washington.edu

Thomas B. Sanford
Applied Physics Laboratory and School of Oceanography
University of Washington
1013 NE 40th Street
Seattle, Washington 98105
Phone: (206) 685-1365 fax: (206) 543-6785 email: sanford@apl.washington.edu

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LONG-TERM GOALS

Our long-term scientific goals are to understand the dynamics and identify mechanisms of small-scale processes in the ocean with the objective of developing improved parameterizations of mixing for ocean models. Internal tides, inertial waves, nonlinear internal waves (NLIWs), and turbulence mixing are all key components to understanding mixing within the stratified ocean. Each of these factors can lead to uncertainty within current ocean models due to their complex interplay. This study focuses primarily on small-scale processes (NLIWs and inertial waves), internal tides, and also key circulation features including cold dome events localized at the continental slope of the East China Sea (ECS) and intrusions generated as the Kuroshio and barotropic tides interact with the continental shelf of the ECS. These small-scale processes and circulation features modulate the temporal, horizontal and vertical spatial structures of the water properties of the ocean. These processes may significantly modify acoustic properties and thus introduce uncertainty into sonar performance and acoustic propagation models. Our ultimate goal is to collaborate with acousticians to identify oceanic processes that alter acoustic properties. A detailed understanding of these properties, mechanism, and dynamics will aid in quantification and assessment of uncertainty in acoustic prediction.

OBJECTIVES

The primary objective of this observational program is the quantification of oceanic physical properties and velocity structure including temporal and spatial structures and their relation to unique processes in the ECS region. The objectives are to quantify and to understand the dynamics of the Kuroshio intrusion and its migration into the southern East China Sea (SECS), to identify the generation mechanisms of the Cold Dome often found on the SECS, to quantify NLIWs and their statistical properties in the SECS, to quantify the internal tidal energy flux in the SECS, to study the effects of

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the Kuroshio front on the internal tidal energy flux, and to provide our results to acoustic investigators to assess the uncertainty in acoustic prediction.

APPROACH

An observational field program was conducted as part of an integrated observational program. Our contribution to the integrated program included two observational components, an array of six subsurface moorings and an array of six EM-APEX profiling floats. The six subsurface moorings (Fig. 1) were deployed off the eastern and northeastern coast of Taiwan 5 August through 12 September 2009; five were located near North Mien Hua Canyon (NMHC) and one on the I-Lan Ridge as part of the extended observational program (Fig. 2). These moorings included 75-kHz Long Ranger ADCPs and a series of temperature/conductivity sensors. The mooring observations are used to quantify the Kuroshio intrusion and migration, internal tidal energy and energy flux, NLIWs and the Cold Dome feature. The EM-APEX floats were deployed from 23 August through 6 September 2009 for a half-month intensive observational period that overlapped with the final half month of the mooring deployments. Six EM-APEX floats were deployed into the North Mien-Hua Canyon and allowed to drift southwest to the operational boundary. At that point they were retrieved and redeployed into North Mien-Hua Canyon. The six EM-APEX floats were deployed a total of 16 times and completed 395 vertical profiles. The floats provided near real-time observations of velocity, temperature and salinity.

WORK COMPLETED

Mooring deployment was successfully completed on 3–9 August 2009. Each mooring was equipped with 9 CTD sensors deployed at depths of 30, 50, 80, 120, 170, 230, 300, 380, and 470 m. One upward-looking 75-kHz Long Ranger ADCP was deployed on each mooring at a depth of 510 m. All six subsurface moorings were successfully recovered on 12–16 September. The six EM-APEX floats were deployed 23 August –7 September near the NMHC. There were 16 EM-APEX float missions. In each float mission, the float cycled between the ocean surface and bottom. When the float surfaced, it reported its GPS position, transmitted data, and received new mission commands. Float trajectories are shown in Fig. 3. While the floats were profiling, we collected ADCP profiles underway and conducted CTD casts on station.

Kevin Taylor, graduate student, presented results of the QPE experiment, entitled “Observations of the Temperature and Salinity Field after Cold Events on the Slope of the East China Sea,” at the QPE workshop in Taipei, Taiwan, at National Taiwan University 2–3 November 2010. The workshop was attended by participants in QPE and aimed at evaluating uncertainty in the sea northeast of Taiwan from an integrated physical oceanography and acoustics perspective. The goal of the workshop was to present the observations from different groups, plan joint analysis and collaboration, and define publications.

QPE collaborators, including us, from Woods Hole Oceanographic Institution, Massachusetts Institute of Technology, University of Washington, Scripps Institution of Oceanography, and National Taiwan University submitted an article to *Oceanography* magazine to be published in a special issue regarding oceanography near Taiwan. Glen Gawarkiewicz is the lead author. Significant results of our work are summarized in the following section.

RESULTS

Two robust intrusions of the Kuroshio appeared on the ECS slope during August 2009; their signature was an abnormally high salinity of 34.6 psu averaged between the1024 kg m^{-3} and 1026 kg m^{-3} isopycnals, characteristic of the Kuroshio subsurface water (Fig. 4a). The average was computed between density surfaces to avoid the effect of the large vertical isopycnal heaving associated with the semi-diurnal internal tides in the region. Vertical displacements of isopycnals due to internal tides on the order of +/–50m were observed; some reached amplitudes greater than 100 m. The velocity fluctuation of semidiurnal internal tides is as large as 0.5 m s^{-1}. The density range 1024–1026 kg m^{-3} was covered consistently by the mooring CTD observations and equated to a mean depth range of 75–270 m for the typical ECS slope water (Fig. 4d). The T/S property at the most southern mooring on I-Lan Ridge revealed first the shallow Kuroshio water (~1023 kg m^{-3}) then deep Kuroshio water (>1024 kg m^{-3}) during 6–15 August (Fig. 4c, red dots).

The largest intrusion was observed in conjunction with Typhoon Morakot (Fig. 4b). A large increase of salinity was observed at the most southern mooring during the evening of 8 August 2009. This was less than one day after Morakot made landfall at Taiwan on 7 August. The large positive salinity anomaly traveled northward through the mooring array at a speed of ~0.8 m s^{-1} (Fig. 4a), which is the speed of the main path of the Kuroshio at a depth of 104 m (Tang et al., 1999). This may suggest that Typhoon Morakot caused the Kuroshio velocity core to meander towards shallower waters. The salinity anomaly persisted longest at the northern most mooring (Fig. 4a, mooring 6, blue salinity record). The intrusion observed by the mooring array was likely partially due to a meander of the main velocity core of the Kuroshio as well as to an intrusion from a branch of the Kuroshio onto the ECS slope, which was situated further to the north.

Concurrent AVISO altimetry data show a change of the absolute geostrophic sea surface velocity in the region of NMHC shifted from northeast to north just after Typhoon Morakot transited through the region. The shift of the absolute geostrophic velocity to north at NMHC supports our observations of increased salinity due to an intrusion of the Kuroshio. A possible explanation for the shelfward movement of the Kuroshio and a northward shift in geostrophic velocity may be attributed to coastal upwelling caused by Typhoon Morakot winds. Southerly winds due to the passage of Typhoon Hai-Tang in the region during the summer of 2005 were suggested to have created coastal upwelling east of Taiwan (Morimoto et al., 2009). The upwelling generated an east–west sea level difference, which in turn generated a northward geostrophic current. The resultant flow could have pushed the Kuroshio towards the ECS shelf (Morimoto et al., 2009).

Rapid salinity anomaly events are present in the deeper layers on moorings QP4, 5 and 6 (Fig. 5). These events appear at time scales of ~10 min in a layer of ~100 m thick, and the magnitude of the salinity variation of ~0.5 psu has an upward salt anomaly and downward fresh anomaly. There is no significant temperature anomaly accompanied with these salinity events. The cause of these anomalies remains under investigation.

A persistent southwestward subsurface countercurrent, relative to the northeastward Kuroshio, was observed along the ECS slope by the five moorings deployed near NMHC and by EM-APEX floats in the region. The current followed primarily isobaths along the slope in deep water, but flowed in a more general southwest trajectory near the surface. A maximum velocity of 0.4 m s^{-1} was observed near 200 m along the 600-m isobath. The water mass properties of the flow at deeper depths appear to be a return of Kuroshio water (Fig. 4c). The surface properties are those of the ECS shelf water.

IMPACT/APPLICATION

In-situ observations conclude that strong internal tides and NLIWs exist on the continental slope of the ECS. Vertical displacements of internal tides on the order of +/–50m were observed; some reached amplitudes greater than 100 m. Two robust intrusions of the Kuroshio appeared on the ECS slope during August 2009. The strongest intrusion was observed in conjunction with Typhoon Morakot. High-frequency strong salinity anomaly events were observed in the lower layers, but their cause is not yet known. These small-scale processes may cause strong sound speed anomalies as well as water mass intrusions affecting sound propagation. To quantify, predict and exploit the uncertainty of acoustic propagation and sonar performance, we need to understand the dynamics of these oceanic processes and their effects on the sound speed. This is the main goal of the proposed experiment.

RELATED PROJECTS

Process Study of Oceanic Responses to Typhoons using Arrays of EM-APEX Floats and Moorings (N00014-08-1-0560) as a part of ITOP DRI: We study the dynamics of the oceanic response to and recovery from tropical cyclones in the western Pacific using long-term mooring observations and an array of EM-APEX floats. Pacific typhoons may cause cold pools on the continental shelf of the East China Sea. The cold pool dynamics are likely related to the Kuroshio and its intrusion as well as the shelf/slope oceanic processes. The cold pool could produce a significant acoustic anomaly that is the focus of the present project.

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Tang, T. Y., Y. Hsueh, Y. J. Yang & J. C. Ma. 1999. Continental slope flow northeast of Taiwan. *Journal of Physical Oceanography* 29:1353-1362.

PUBLICATIONS

Gawarkiewicz, G. et al. 2011. Can we accurately predict circulation and internal waves northeast of Taiwan? Chasing uncertainty in the Cold Dome. *Oceanography* submitted on 5 September 2011.

HONORS/AWARDS/PRIZES

Gledden Sr. Visiting Fellowship at U. Western Australia (Sanford, October 2008).

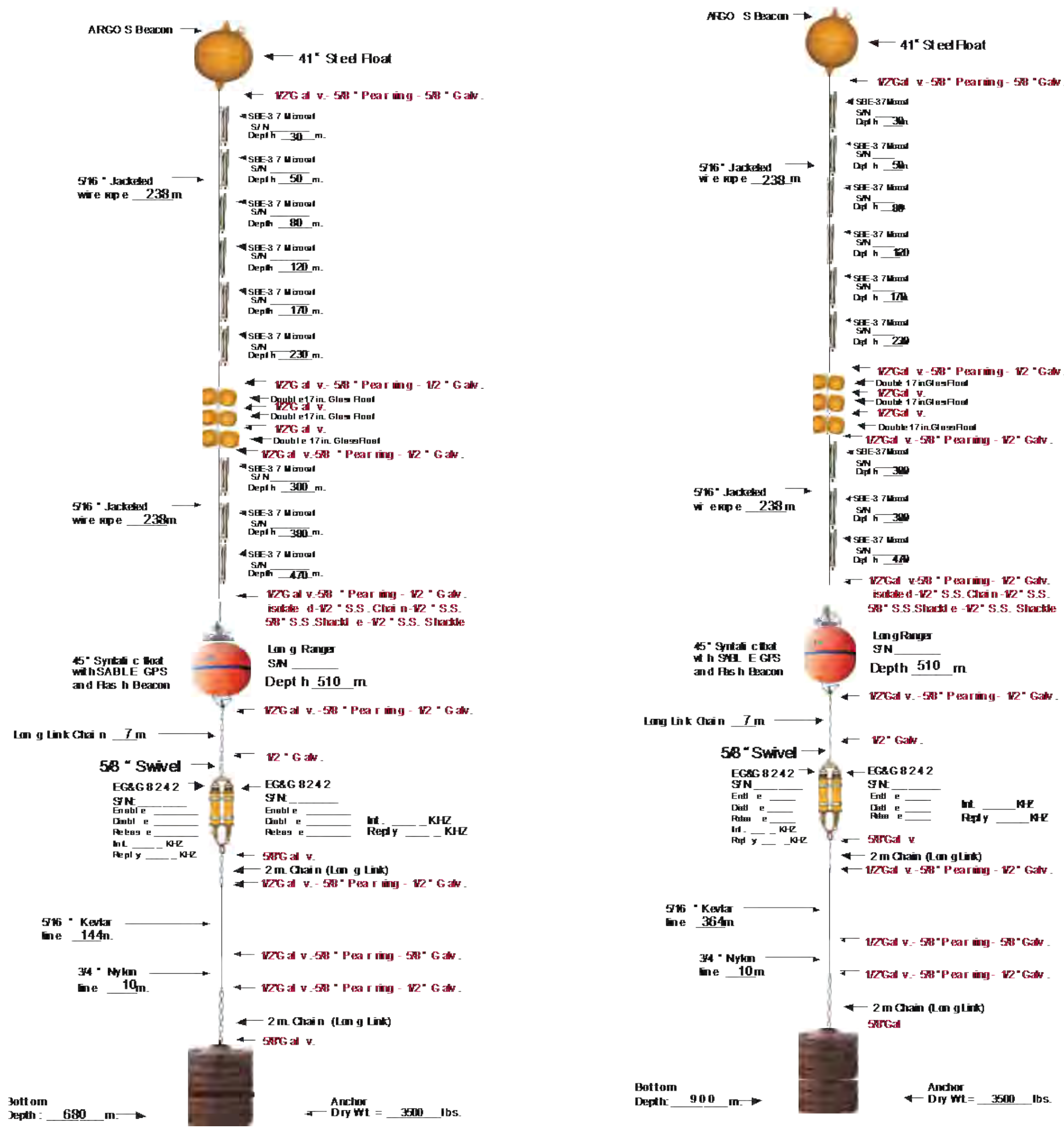

Figure 1. Schematic diagram of QPE shallow mooring (left) and deep mooring (right). Four shallow moorings (680-m water depth) and two deep moorings (900-m water depth) were deployed during the QPE experiment. Each mooring is equipped with one 75-kHz Long Ranger ADCP, nine CTD sensors, dual EG&G acoustic release, one steel float at 30 m, one syntactic float at 510 m, six glass floats, one Argos beacon and one submersible Iridium transmitter (SABLE).

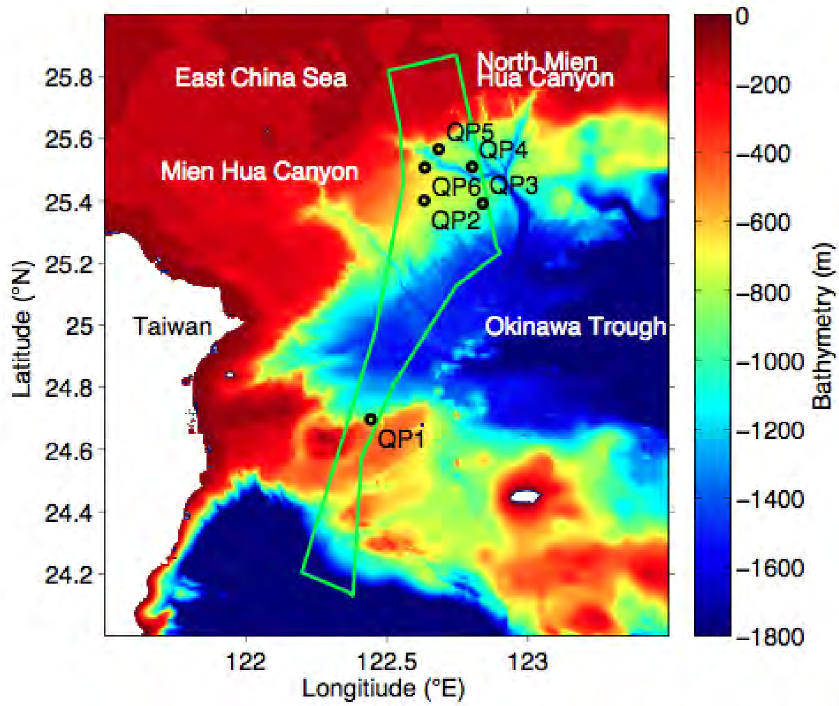

Figure 2. Bathymetry map of the southern East China Sea. Positions of six moorings, labeled QP1-6. Operational boundary is shown in green.

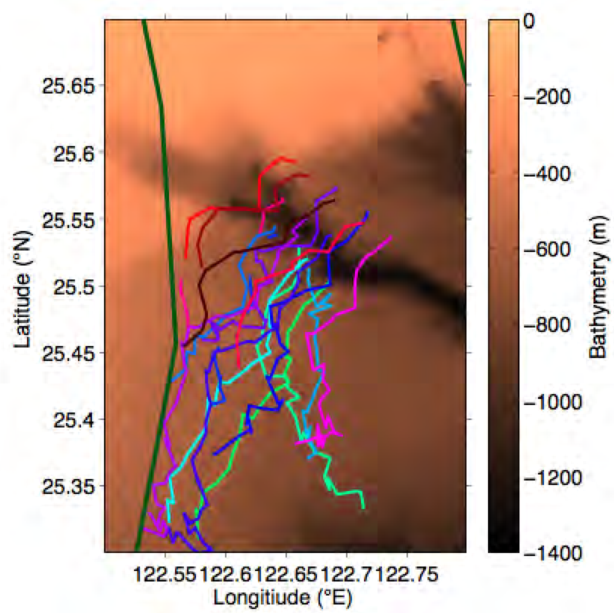

Figure 3. Trajectories of EM-APEX floats in QPE experiment. There are 16 float missions. Floats drift in a southwestward direction. Operational boundary is shown in dark green.

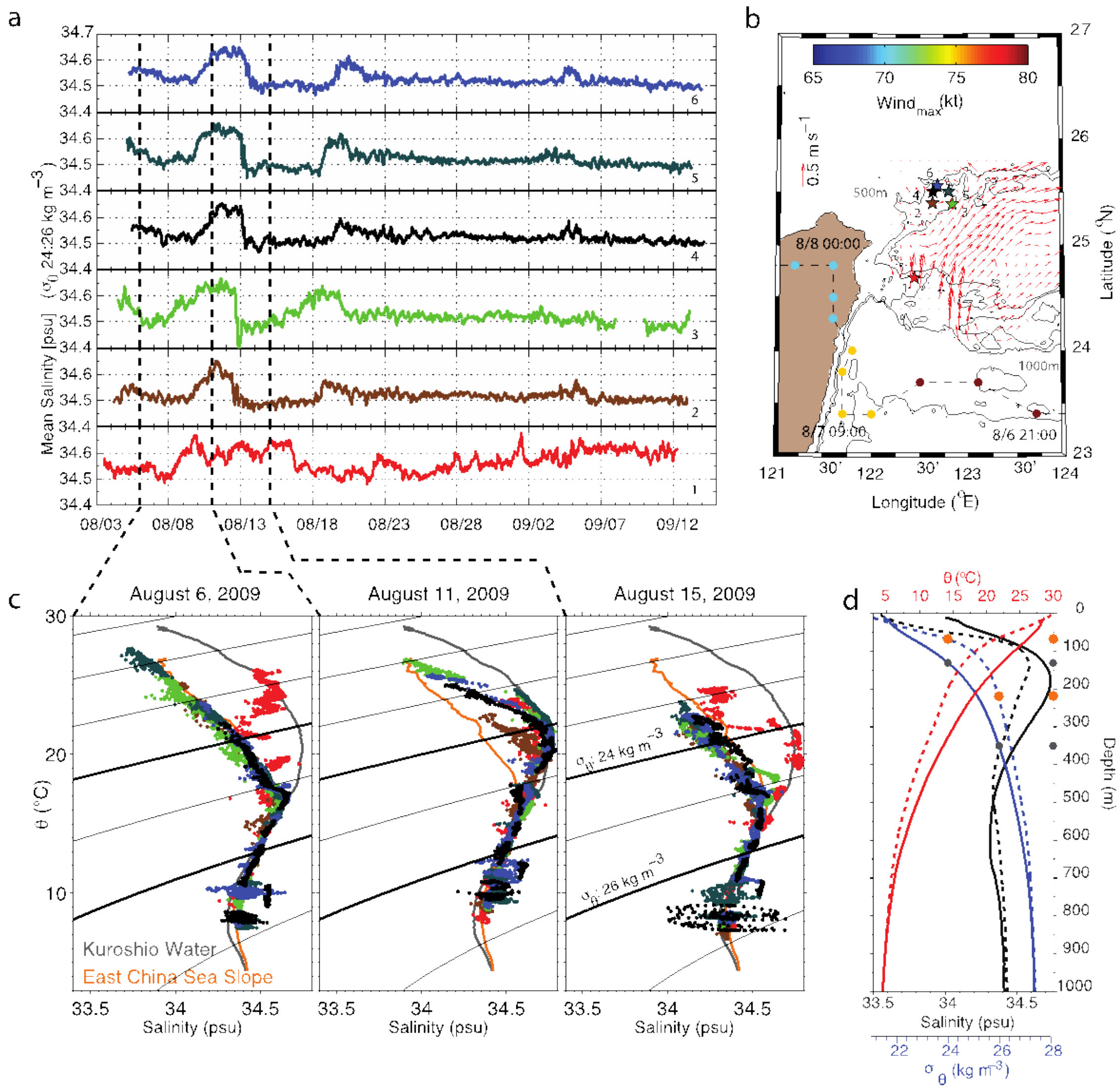

Figure 4. (a) Temporal variation of salinity averaged between σ_θ 24 kg m^{-3} and 26 kg m^{-3} at six moorings deployed east and northeast of Taiwan. (b) Horizontal velocity averaged from the sea surface to either the bottom or 1000 m depth from gliders in 0.1° latitude × 0.1° longitude grid points (red velocity arrows), Typhoon Morakot track and maximum wind speed (filled circles color-coded by maximum wind speed), and six mooring locations (colored stars) that are color-coded and numbered to correspond to mean salinity records in (a). (c) Potential temperature and salinity plot before Typhoon Morakot (left), immediately after Typhoon Morakot (center), and several days after Typhoon Morakot (right). Colored dots correspond with color-coding of moorings (b, stars) and mean salinity records (a). Kuroshio T/S property (solid gray line) was collected from gliders; East China Sea slope water T/S property (solid orange line) was collected from EM-APEX floats. (d) Average vertical profile of salinity (black), potential temperature (red), and potential density (blue) for the Kuroshio collected by gliders in Okinawa Trough (solid lines) and the East China Sea slope collected by EM-APEX floats (dashed lines). Average depth associated with σ_θ 24 kg m^{-3} and 26 kg m^{-3} for the Kuroshio (gray) and the East China Sea Slope (orange) shown with colored circles.

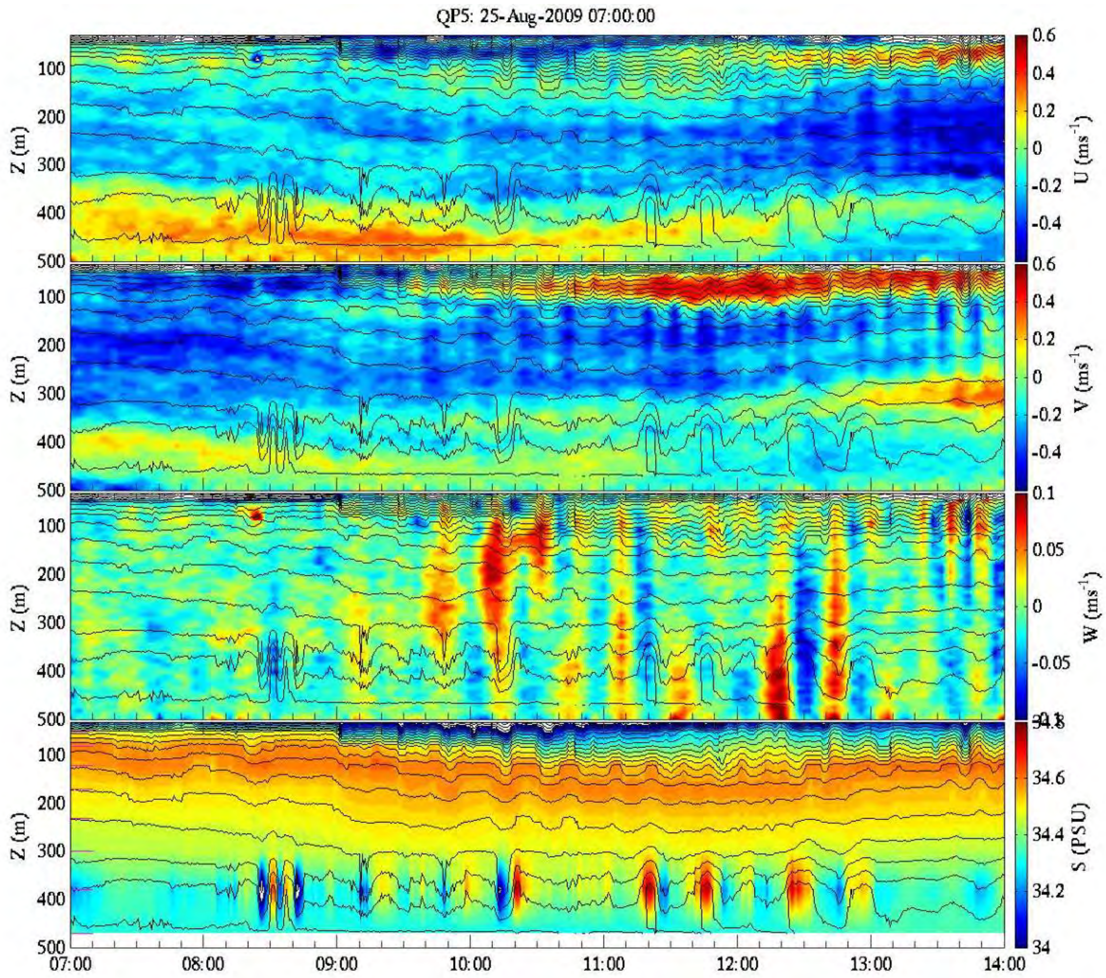

Figure 5. Example of rapid salinity events in the deeper layers of QP5 mooring. These salinity events happen at a time scale of minutes and appear in pairs, i.e,. salty and fresh. They have a vertical scale of ~100 meters. They are associated with vertical motions suggested by the vertical displacement of isopycnal surfaces and some with the direct vertical velocity measurements.